Veget Hist Archaeobot
DOI 10.1007/s00334-012-0380-0

ORIGINAL ARTICLE

Vegetation dynamics during the early to mid-Holocene transition in NW Malta, human impact versus climatic forcing

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Received: 11 May 2012 / Accepted: 10 October 2012

Abstract A pollen diagram was constructed for the early- to mid-Holocene transition (ca. 7350–5600 cal. B.P./5400–3650 B.C.) from the Burmarrad ria located in NW Malta. The vegetation at ca. 7350–6960 cal. B.P./5400–5010 B.C. was characterized by an almost tree-less steppe-like open landscape. Early Holocene dry climatic conditions were most probably due to intensification of the subtropical monsoon circulation that strengthened the subtropical anticyclonic descent over the central Mediterranean and blocked the penetration of humid air masses from the North Atlantic Ocean. At ca. 6950 cal. B.P./5000 B.C., the steppe-like vegetation was suddenly replaced by a Mediterranean evergreen forest or dense scrub dominated by *Pistacia* cf. *lentiscus* trees. This event, which has simultaneously been recorded in southern Sicily, was most probably caused by the southward shift of the ITCZ permitting the eastward movement of the North Atlantic cyclonic systems. Traces of human activities are evident in the pollen diagram since the beginning of the record but become more pronounced from the onset of the Temple Cultural Phase at ca. 6050 cal. B.P./4100 B.C. with a gradual decline of tree pollen. We suggest that the early- to mid-Holocene vegetation transformation was mainly controlled by a regional climatic change that occurred in a landscape only slightly impacted by human activities.

Keywords Pollen analysis · Monsoon intensification · Neolithic · Temple cultural phase · Mediterranean · Evergreen *Pistacia*

Communicated by J.-L. de Beaulieu.

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Introduction

Recent palaeoenvironmental reconstructions from the central Mediterranean attest to contrasting patterns of hydrological evolution during the early- to mid-Holocene. Spatially, these are characterized by marked west versus east and north- versus south-central Mediterranean disparities (Magny et al. 2011, 2012; Roberts et al. 2011; Vannière et al. 2011). The main dividing lines broadly run through the Balkans, southern Italy and Tunisia, approximately correlating with 40°N (Magny et al. 2011; Roberts et al. 2011). These contrasting spatial patterns of Holocene hydrology have been attributed to differences in seasonal precipitation (Magny et al. 2012). Discrepancies in palaeo-records are, for instance, attested between vegetation and lake-level records of the Italian Peninsula (Drescher-Schneider et al. 2007; Magny et al. 2007; Sadori et al. 2011) and those of southern Sicily (Sadori and Narcisi 2001; Noti et al. 2009; Tinner et al. 2009). However, with the exception of Sicily, the number of multi-proxy palaeoenvironmental investigations, especially in the southern Mediterranean including Malta and North Africa, are limited to a just few records (e.g. Ben Tiba and Reille 1982; Stambouli-Essassi et al. 2007; Fenech 2007), many of which lack

Published online: 30 October 2012

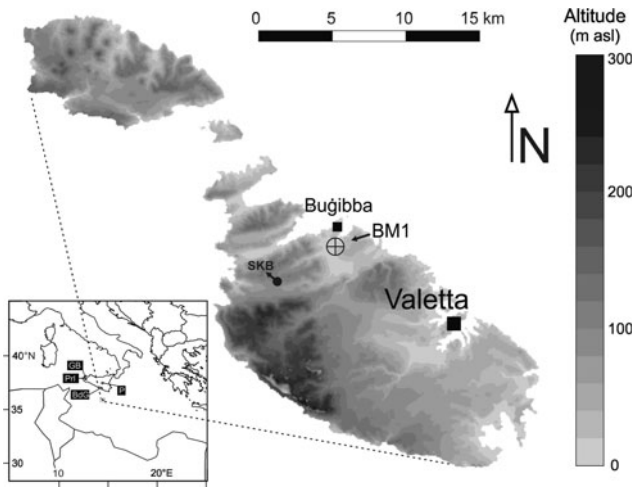

Fig. 1 *Shaded relief map* of the Maltese Islands with the location of the studied core BM1. *SKB* Skorba temple site, *Prl* Preola, *GB* Gorgo Basso, *BdG* Biviere di Gela, *P* Lago di Pergusa

robust chronological frameworks (Sadori et al. 2011) or give fragmentary records of past climate and vegetation change (Hunt et al. 2011; Mercuri et al. 2011). The Maltese Islands (Fig. 1) are located in a key climatic position to evaluate the palaeohydrological evolution of the central Mediterranean region because they lie on the presumed hydrological hinge line (e.g. Roberts et al. 2011).

The Maltese islands have had a complex Quaternary faunal history characterized by the presence of extinct species of dwarf hippopotamus and pygmy elephants (Hunt and Schembri 1997). During the Pleistocene, the vegetation and flora of these islands were markedly different from today (e.g. Hunt 1997). Occurrences of presumed relict populations of the conifer *Tetraclinis articulata* provide an example of a once different flora, which has altered due to both climatic changes and anthropogenic activities (Haslam et al. 1977). On the other hand, Maltese ecosystems have been exploited by human societies since the sixth millennium B.C. when the islands were occupied by the first Neolithic communities (e.g. Malone et al. 2009). The extent to which Maltese ecosystems were impacted by man during Neolithic times (Table 1) is, however, equivocal (Fenech 2007, pp. 104–105).

Our knowledge of the vegetation and floral history of the Maltese Islands is however very scant due to the lack of lake and peat bogs and the rarity of other suitable palaeoecological archives. A detailed description of the Quaternary deposits of the Maltese Islands and their palaeoenvironmental potential has been summarized in Hunt (1997) and Hunt and Schembri (1997). The available palaeovegetation works are limited to pollen analysis of a tufa deposit of unknown Pleistocene age (Hunt 1997), a few archaeobotanical reports (e.g. Metcalfe 1966) and a pollen record from Marsa in eastern Malta (see the pollen data of F. Carrol and C. Hunt presented in Fenech 2007). The latter diagram gives a general image of vegetation change in eastern Malta during the late-Pleistocene to late Holocene. However, poor pollen preservation, chronological inversions and rapidly varying sedimentation rates, especially in the early- to mid-Holocene, make the interpretation of this diagram a difficult task (Fenech 2007).

In this study, a pollen record is presented from northwestern Malta (Fig. 1) for the early- to mid-Holocene transition (ca 7350–5570 cal. B.P.). This time interval corresponds to a significant climatic change and cultural phase in the south-central Mediterranean region (e.g. Noti et al. 2009; Tinner et al. 2009). Our main objectives are:

(1) To reconstruct the vegetation dynamics during the early to mid-Holocene transition in NW Malta compared with other regional pollen records, particularly those from Sicily.
(2) To attempt to disentangle the human versus climatic forcings in shaping landscape and vegetation during this transition.

In the absence of permanent wetland systems such as lakes and peat bogs, we have used a fine-grained ria sequence from northwestern Malta (Burmarrad). We demonstrate the high potential of these sequences for palaeoenvironmental reconstruction in semi-arid coastal environments.

Setting

Climate

Meteorological data from Valletta (35°54′N, 14°31′E; 70 m a.s.l.) provide a representative picture of the general climatic/bioclimatic context of the Maltese Islands (Fig. 2; inset). Mean annual precipitation (P) is about 519 mm mainly falling from October to April, and mean annual temperature (T) is 19 °C. The degree of continentality (Ic) is low (13.8 °C) with high mean temperatures for both the hottest (26.1 °C) and coldest (12.3 °C) months of the year. The average minimum absolute temperature for the coldest month is also high (5 °C), indicating the near absence of frosts on the islands. Malta has a Mediterranean Pluviseasonal-Oceanic bioclimate in the Global Bioclimatic Classification System, which is the most prevalent bioclimate in the Mediterranean Basin (Rivas-Martínez et al. 1999, 2004a). This bioclimate is characterized by low continentality (≤21 °C), relatively high precipitation during the growing season, and 3–10 dry months in which $P \leq 2T$. Malta displays the same bioclimatic features as southern Sicily (see bioclimatic maps in Rivas-Martínez et al. 2004a, b).

Vegetation

The Maltese Islands fall within the Thermo-Mediterranean vegetation belt (Haslam et al. 1977; Fig. 1.4 in Quézel and

Table 1 Major prehistoric cultural phases in the Maltese Islands with ages (B.C.) attributed by different authors and a summary description of main cultural events

	Phase	Cassar 2000	Trump 2002	Blouet 2007	Fenech 2007	Cassar et al. 2007	Malone et al. 2009	Main Characteristics of Phase
Temple Phase (Copper Age)	Tarxien	2500-3000	2500-3150	2500-3000	2470-3500		2400-3100	Large additions to Tarxien and Mnajdra temples. No parallels to Sicily. Temple-building complexes. Communal hypogeal
	Salfieni	2900-3000	3000-3300					Transitional stage. No parallels outside Malta. Malone et al. (2009) place Salieni within Tarxien period
	Ggantija	3000-3600	3200-3600	3000-3600	2940-3360		3100-3600	Construction of first Megalithic structures. No parallels outside Malta. Ochre no longer lavished over bodies. Earliest Temple structures, oval houses. Final use of small rock cut tombs
	Mgarr	3600-3800	3600-3800	3600-3800	2900-3700		3600-3800	No parallels outside Malta. First lobed structures, plaster floors
	Zebbug	3800-4000	3700-4100	3800-4100	3050-4350		3700-4100	Clear break in development phase between Red Skorba and Zebbug. New group of settlers from Sicily, parallels to San Cono-Piano Notaro culture. Rock-cut tombs and oval houses
Neolithic	Red Skorba	4000-4400	4100-4400	4100-4400	3650-4350		4100-4400	Cultural continuity with Grey Skorba. Red slip parallels with Diana culture in Sicily/Lipari (Bonanno 2005). Oval houses, shrines, mud brick used
	Grey Skorba	4400-4500	4400-4500	4400-4500			4400-4500	No parallels in Sicily. The date derived from Trump (1966) at Skorba. Open settlements
	Ghar Dalam	4500-5000	4500-5000	4500-5200	4100-5500	4000-5000	4300-5000	Date first published at 4190 B.C. corrected with tree ring dates to 5266-4846 B.C. from a deposit alongside a wall at Skorba (Trump 1966). Pottery similarities to Stentinello, Sicily. First known human settlement (agricultural life-style). Rock-shelters and open settlements

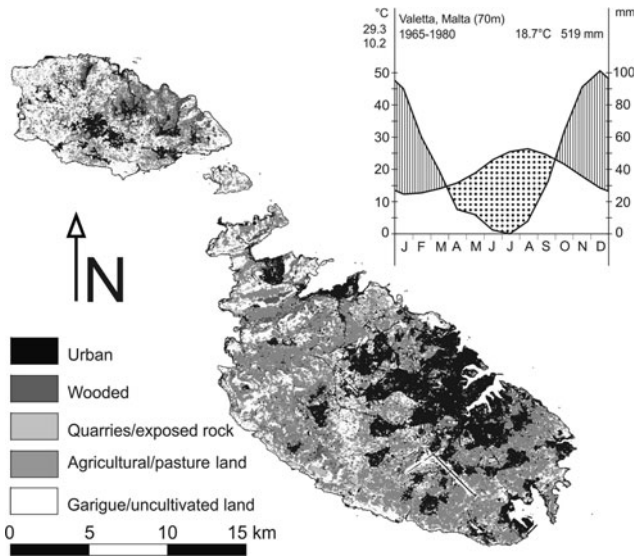

Fig. 2 Map showing the distribution of five major vegetation types and land-use units of the Maltese Islands. The inset picture represents the climate diagram of Valetta based on data derived from the website of World Bioclimatic Classification System at: http://www.globalbioclimatics.org

Médail 2003; Rivas-Martínez et al. 2004b). This belt is characterized by mean temperature minima for the coldest month (m) of more than 3 °C and a tree vegetation generally dominated by *Olea europaea*, *Ceratonia siliqua* and *Pistacia lentiscus*. *Pinus halepensis*, sclerophyllous oaks, sometimes accompanied by deciduous oaks, may also be present (Quézel and Médail 2003). Detailed descriptions of the vegetation and flora of the Maltese Islands are found in Haslam et al. (1977) and Lanfranco (1995) among others. A more simplified picture of the vegetation is, however, given by Schembri (1997) who divides the Maltese vegetation into woodlands, maquis, garrigues, steppes and several small vegetation communities. It has been suggested that woodlands were severely impacted by human activities over many millennia (Haslam et al. 1977; Grech 2001). The woodland remnants are nowadays restricted to a few localities, particularly some small stands dominated by *Quercus ilex*. This latter tree is supposed by many botanists to be the potential forest vegetation of the Maltese Islands. Maquis are the impoverished scrub communities mainly formed after the degradation of the woodlands due to forest cutting, overgrazing and soil erosion. The semi-natural maquis dominated by *Ceratonia siliqua*, *Olea europaea*, *Pistacia lentiscus* and several other small trees/shrubs have survived in naturally protected and inaccessible habitats such as the Globigerina valley sides. Garrigues constitute the most characteristic vegetation type of the Maltese Islands predominately having developed on the karstic limestone plateaux of inland areas. They are open communities dominated by dwarf shrubs such as *Erica multiflora*, *Teucrium fructicans*, *Thymbra capitata*, and the endemic *Euphorbia melitensis* and *Anthyllis hermanniae* ssp. *melitensis*, accompanied by a number of annuals and perennials. Garrigues may occur naturally but most often form in disturbed forest and maquis with intensive soil erosion. Other vegetation communities, covering much smaller territories, include coastal communities, rupicolous communities rich in endemics, freshwater communities and ruderal communities associated with arable and waste lands. On the Maltese Islands, the flora and vegetation have long been impacted by human activities, at least since the beginning of the fifth millennium B.C. (Haslam et al. 1977). Indeed, about 40 % of the Maltese flora is composed of weeds of cultivated lands and wastelands and there are commonly no sharp boundaries between the species of disturbed and undisturbed areas. The natural or semi-natural vegetation can only be found in small stands restricted to some sheltered habitats such as on the Globigerina valley sides. Many of the native Maltese trees and shrubs still occur in these sheltered habitats including *Crataegus* spp., *Ceratonia siliqua*, *Pistacia lentiscus*,

Table 2 Radiocarbon ages for six samples from the core BM1, NW Malta

Sample number	Lab code	Depth (cm)	^{14}C age (year B.P.)	Calibr. age (cal. year B.P.)	Cal. age range/ probability ()	Material dated
BM1/64A	SacA-11663	845	4563 ± 30	5120 ± 65	5055–5186 (0.52)	Charcoal
				5292 ± 28	5264–5321 (0.43)	
BM1/80	Poz-42441	1005	5410 ± 40	6236 ± 60	6176–6296 (0.89)	Charcoal
BM1/93	SacA-11668	1117.5	6115 ± 30	6964 ± 67	6897–7031 (0.72)	Peat
				7125 ± 30	7095–7156 (0.21)	
BM1/100	SacA-11669	1215	6500 ± 30	7441 ± 30	7411–7472 (0.62)	Charcoal
				7362 ± 37	7325–7399 (0.38)	
BM1/121	Poz-42439	1415	6650 ± 60	7521 ± 88	7433–7609 (1)	Charcoal

Calibrated dates are reported as means of the 2σ-ranges with highest probability. Possible age-ranges with highest probabilities (in parentheses) are also reported as a separate column (2σ-ranges). ^{14}C ages were calibrated by CALIB 6.1.1 based on IntCal09 calibration dataset (Reimer et al. 2009)

Quercus ilex, *Rhamnus lycioides* ssp. *oleoides* and *Tetraclinis articulata*, the latter being a presumed relict species (Haslam et al. 1977).

Materials and methods

Coring, chronology, and stratigraphy

Four cores (BM1–BM4) were recovered from the Burmarrad floodplain (NW Malta) using a percussion corer (Beretta drilling machine) in spring 2008 and 2010 (Fig. 1). The site was selected based on preliminary exploratory drillings conducted during an earlier project (Gambin 2005) that revealed the presence of a relatively thick and continuous terrestrial-marine sediment infill. After stratigraphical descriptions, core BM1 (14 m long) was subsampled every 5–10 cm for further pollen and sedimentological analyses. Five radiocarbon ages were obtained to construct the age-depth model. ^{14}C ages, reported in Table 2, were calibrated in Calib 6.1.1 using IntCal09 (Reimer et al. 2009). The age-depth model (Fig. 3) was constructed using non-Bayesian modeling in the R-based package of CLAM (Blaauw 2010). The age-depth model shows an age-range of 8465–7763 cal. B.P. for the base of the core at 1,400 cm. However, in this study, only the calibrated chronology for the interval of 12–9 m has been shown (see below). This interval starts with upper estuarine dark grey silts (1,200–1,115 cm) which suddenly change into a fine-grained peat formed in a closed freshwater wetland system. At about 1,105 cm, lower estuarine grey silts replace the wetland organic deposits and continue up to about 975 cm where they grade into the open marine grey shelly sands.

Pollen analysis

A series of tests was conducted all along the core to locate the polliniferous sections of the sample. The section 1,200–900 cm presented good pollen preservation and was pollen-rich. We focused our attention on this section with a sampling resolution of 10 cm. Extraction of pollen grains and Non-Pollen Palynomorphs (NPPs) was undertaken using 10 % HCl, 40 % HF, 37 % HCl and acetolysis (e.g. Moore et al. 1991). Pollen identification was performed with the help of the IMBE's pollen reference collection and the pollen atlases of Europe and North Africa (Reille 1992, 1995, 1998). The *Ostrya*-type pollen curve may represent both *Carpinus orientalis* (Beug 2004) and *Ostrya* and the *Quercus* pollen curve is the sum of *Q. ilex*-type and *Q. pubescens*-type. Dinoflagellates were determined by Laurent Londeix (EPOC, University of Bordeaux); NPPs were identified using Cugny (2011), Mudie et al. (2011) and Haas (1996). Pollen percentages were calculated in TILIA and the pollen percentage diagram (Fig. 3) was constructed using TGView software (Grimm 2004–2005). In calculating pollen percentages of upland plants i.e. trees, shrubs and herbaceous species growing on well-drained soils, aquatic and hygrophilous plants (Cyperaceae, spores, *Typha*/*Sparganium*-types) were excluded from the pollen sum. However, in calculating the pollen percentages of these latter plants, they were included in the Total Pollen Sum. Hence, the final pollen diagram is a synthetic diagram in which the pollen curves calculated with two above methods are placed together. The pollen diagram was subdivided into Local Pollen Assemblage Zones (LPAZs) by applying stratigraphically-constrained cluster analysis to percentage data using CONISS software included in the TILIA package (Grimm 1987, 2004–2005). Pollen concentration values were also calculated by the addition of *Lycopodium* tablets (Stockmarr 1971) to check that the pollen percentage variations were not an artifact of low pollen concentration values. PCA analysis was applied to pollen percentages using XLSTAT v. 2009.3.02 (Addinsoft, Paris 1995–2009) and the axis 1 (18 % of variability) scores for different samples were plotted against the depth in the pollen diagram (Fig. 3).

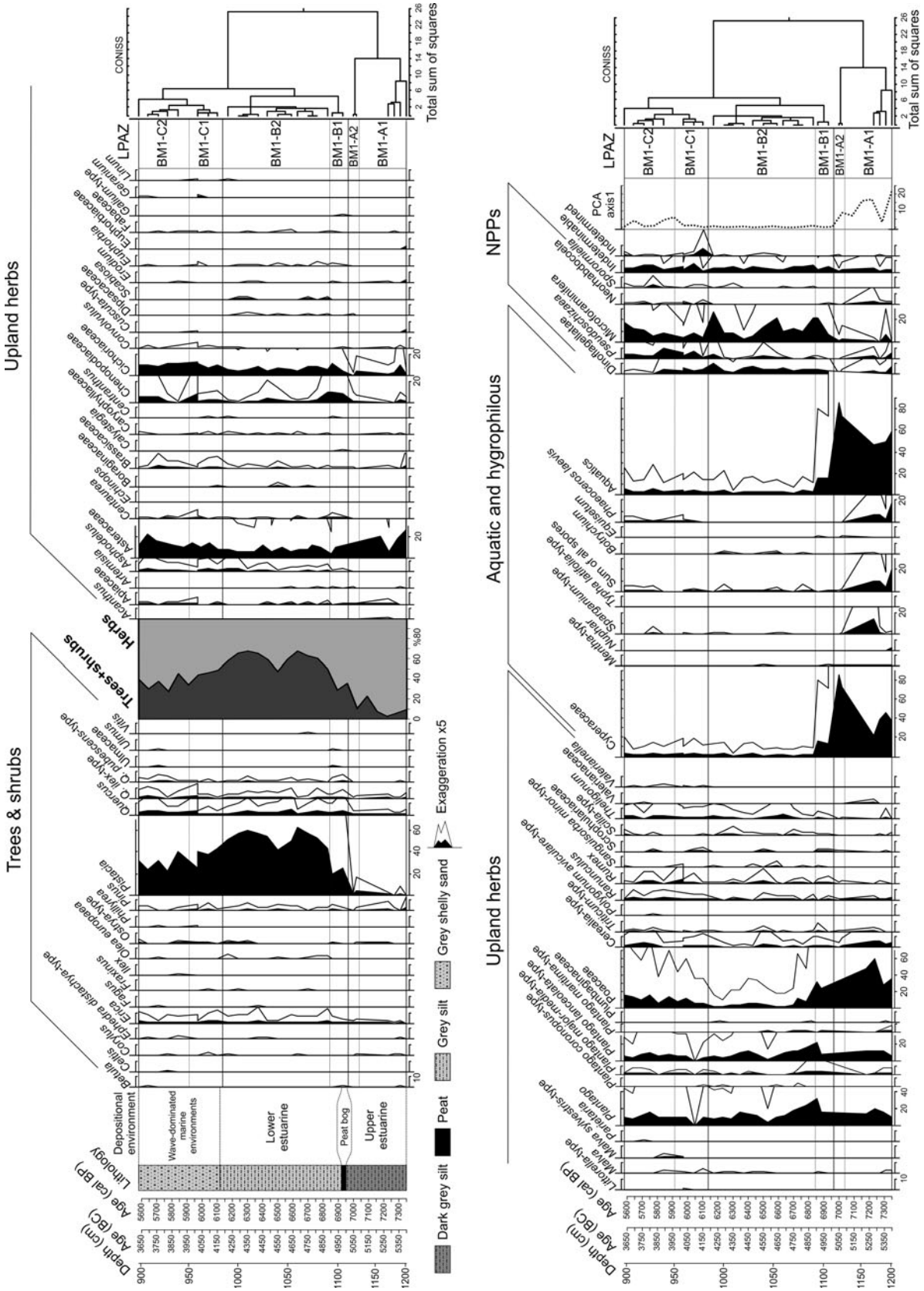

Fig. 3 Pollen percentage diagram of the core BM1. Pollen of aquatic plants, spores and non-pollen objects are excluded from the pollen sum

Chironomid analysis

A few sediment samples, one from the base of the core and the others from the peaty interval (1,115–1,110 cm) were analyzed for chironomid capsules. This additional technique was used to understand the hydrological and physical characteristics of the depositional setting during the study period. The samples were treated in hot KOH for 20 min followed by kerosene flotation.

Results

Fossil data

The pollen percentage diagram of core BM1 is presented in Fig. 3. The pollen concentration curves (not shown in this paper) displayed similar trends to percentage curves showing that percentages were not biased by differential preservation and other taphonomic processes and that the sedimentation rate remained relatively constant. On the right of the diagram, the PCA Axis 1 values were plotted, showing a good match with the variations of aquatic plants. Based on the stratigraphically-constrained clustering (Grimm 1987, 2004–2005) of all pollen percentage data (Fig. 3), three Local Pollen Assemblage Zones (LPAZs) and several subzones were distinguished. The boundaries of the LPAZs are almost perfectly correlated to the lithological boundaries. Percentage changes are mostly explained by the aquatic/hygrophilous pollen and NPPs whose variations are mainly mediated by local hydrological modifications which also control the nature of deposited sediments.

LPAZ BM1-A

The base of the BM1 pollen diagram is dated to ca. 7350 cal. B.P. (1,200 cm depth). During this pollen zone (ca 7350–6960 cal. B.P./5400–5010 B.C.), arboreal pollen percentages are very low contrary to those of aquatic plants, the pollen of which dominates the spectra and reaches its highest values along the whole core (Fig. 3). Relative pollen variations of aquatic/hygrophilous plants account for the further subdivision of LPAZ A into two subzones. LPAZ BM1-A1 is characterized by high values of Poaceae (most probably *Phragmites* judging from the dominance of pollen <30 μm in size), Cyperaceae, and *Sparganium*-type (*Typha angustifolia* and/or *Sparganium*) pollen and abundant spores dominated by *Phaeoceros laevis*. Neorhabdocoela also display significant values during LPAZ BM1-A. By contrast, LPAZ BM1-A2 shows a significant peak of Cyperaceae.

LPAZ BM1-B

The onset of this pollen zone (ca 6960–6140 cal. B.P./5010–4190 B.C.) is characterized by sudden lithological and palynological changes at around 6960 cal. B.P. The dark grey silt suddenly changes into a 10 cm thick peat deposit (Fig. 3). At the same time, the arboreal pollen abruptly increases and aquatic/hygrophilous pollen taxa decline. *Pistacia* pollen predominates in the pollen spectra with percentages attaining up to 64 %. Other trees and shrubs have very low pollen values and discontinuous curves excepting *Erica* (most probably *E. multiflora*) and *Quercus* (both *Q. ilex*-type and *Q. pubescens*-type). Chenopodiaceae pollen increases to form a peak during the deposition of subzone BM1-B1. Many upland herbaceous pollen taxa appear or start to form relatively continuous curves during and mostly at the beginning of this zone. Examples include *Asphodelus*, *Centaurea*, Dipsacaceae, *Euphorbia*, Fabaceae, *Scilla*-type, *Malva*, *Sanguisorba minor*-type and *Theligonum* (Fig. 3). The BM1-B zone is also characterized by the appearance or increase of a number of NPPs such as dinoflagellates, microforaminifera and the fungal spores of *Sporormiella*.

Most of the dinoflagellate cysts encountered in the BM1 palynological slides belonged to the genus *Spiniferites* (e.g. *S. ramosus*, *S. mirabilis*, *S. hyperacanthus*) with a few occurrences of *Lingulidinium machaerophorum*, *Operculodinium israelinium* and many Tertiary fossil specimens most probably deriving from the Tertiary marine formations of the island. In this study, all modern dinocysts have been grouped together in a single curve (Fig. 3). The above dinoflagellate assemblage suggests a connection to the sea in Burmarrad during the deposition of the majority of the studied core section excepting the peaty layer, especially during the time intervals of 6960–5840 cal. B.P./5010–3890 B.C.

LPAZ BM1-C

The beginning of this pollen zone (ca 6140–5570 cal. B.P./4190–3620 B.C.) also corresponds with a lithological change from grey silts into a sandy unit with shell fragments (Fig. 3). The trees and shrubs start to decrease during LPAZ BM1-C1 and reach lower values during LPAZ BM1-C2. During BM1-C, many herbaceous pollen taxa indicate slight increases including Asteroideae, *Centaurea*, Brassicaceae, Chenopodiaceae, *Malva*, *Plantago major-media*-type, Cerealia-type (e.g. *Triticum*-type), *Rumex*, *Ranunculus* and *Valerianella*. Among the NPPs, *Sporormiella* significantly increases while *Pseudoschizaea* and *Phaeoceros laevis* increase again and reach comparable values to those in LPAZ BM1-A.

Chironomid content

Only the peaty layers yielded chironomid capsules. The number of capsules was very low ($n = 9$), below the statistically significant level for quantitative reconstructions ($n = 50$; Heiri and Lotter 2001). However, as the identified taxa provide significant environmental information, they are reported and discussed in this paper. The observed chironomid capsules were identified as belonging to the following taxa: five specimens of *Paratendipes albimanus*-type, one specimen of *Microtendipes pedellus*-type, one specimen of *Polypedilum* and two specimens of the group *Parametriocnemus/Paraphaenocladius*.

Discussion

Early- to mid-Holocene upland vegetation dynamics in NW Malta in relation to regional climate change

The vegetation of NW Malta at ca. 7350–6960 cal. B.P./5400–5010 B.C. was characterized by an almost treeless landscape. Very low pollen percentages of *Pistacia*, *Erica* and *Quercus* (both *Q. ilex*-type and *Q. pubescens*-type) suggest that these trees were present as small stands on the island. Open steppe-like vegetation has also been reported for the early Holocene, at least for a millennial-scale interval of time before ca. 7000 cal. B.P., of coastal Sicily and SE Spain (Calò et al. 2012; Noti et al. 2009; Pantaléon-Cano et al. 2003; Tinner et al. 2009). The vegetation record at Lago di Pergusa, inland Sicily, located at higher elevations (674 m a.s.l.) and with a wetter and cooler climate than that of the coastal zone (Calò et al. 2012), shows nearly continuous re-afforestation since the beginning of the Holocene, however with forest development having been slower than expected (Sadori et al. 2008). Almost all the microscopic charcoal records of Sicily show higher than average fire activity during 8500–7500 cal. B.P. (Vannière et al. 2011). This is particularly prominent in Gorgo Basso (Tinner et al. 2009), Lago di Pergusa (Sadori et al. 2008) and Lago Preola (Calò et al. 2012) and suggest more intense summer dry conditions. At ca. 6960 cal. B.P., a Mediterranean evergreen forest, or dense scrub, started expanding, at least in the study area. Simultaneously, fire activity displays a decreasing trend in Sicilian records (Calò et al. 2012; Sadori et al. 2008; Tinner et al. 2009). This vegetation community was predominately *Pistacia* trees but also contained *Erica* and evergreen oak (*Q. ilex*-type). The sporadic and low-percentage occurrences of *Olea* and *Fraxinus* pollen may be partly explained by small stands on the island but also by long-distant transportation from neighboring lands such as Sicily. It should be noted that archaeobotanical finds from the Ghar Dalam cultural phase (ca. 6950–6250 cal. B.P./5000–4300 B.C.; see Table 1) demonstrate that deciduous trees including *Fraxinus, Cercis siliquastrum* and *Crataegus* were also present on the island (Metcalfe 1966) during the forest expansion phase (Fig. 3; LPAZ BM1-B2). This suggests that the forest composition on Malta had a more diversified floristic composition than is reflected by these pollen spectra. However, the forest composition was certainly less diverse than the Sicilian forests judging from the more diverse tree pollen assemblages in Sicilian pollen records (Calò et al. 2012; Noti et al. 2009; Sadori and Narcisi 2001; Tinner et al. 2009). This low diversity is most probably related to the smaller size and lower altitudinal variation of Malta compared to Sicily that created fewer differentiated ecological niches.

Comparison of the BM1 pollen record with the Gorgo Basso diagram in southwestern Sicily (Tinner et al. 2009) shows a remarkable chronological correlation between the abrupt expansions of *Pistacia* woodlands/scrub on the two islands (Fig. 4). In Lago Preola, located a few kilometres to the NW of Gorgo Basso, *Pistacia* expansion is recorded at ca. 7300 cal. B.P. (Calò et al. 2012). Further east, at Bieviere di Gela, also located in a coastal area of southern Sicily, the *Pistacia* expansion occurred some 200 years later at ca. 6700 cal. B.P. (Noti et al. 2009). The increase of *Pistacia* pollen at the inland site of the Lago di Pergusa was also contemporaneous with those in coastal Sicily (Fig. 6 in Sadori and Narsici Sadori and Narcisi 2001). It is known that *Pistacia* is under-represented in modern pollen assemblages (e.g. Wright et al. 1967; van Zeist and Bottema 1977). In the Zagros Mountains of western Iran, the highest values of *Pistacia* pollen reach only 4.5 % even where *Pistacia* trees form a significant tree cover (Wright et al. 1967). However, in contrast to some Mediterranean species such as *P. lentiscus* and *P. terebinthus*, pistachio species of Iran are deciduous and thus caution should be taken in generalizing their low pollen production to Mediterranean evergreen species of the genus. *Pistacia* pollen in the BM1 pollen diagram attains very high values up to >60 %, which is on average 15–20 % higher than those for Gorgo Basso and Biviere di Gela (Noti et al. 2009; Tinner et al. 2009). Such high pollen values suggest that dense *Pistacia* woodlands or scrubs dominated the NW Maltese landscapes during ca. 6960–5600 cal. B.P./5010–3650 B.C. Ecological interpretation of *Pistacia* pollen variations, however, depends on the pistachio species that has produced the pollen because different species indicate different bioclimatic and ecological conditions (Sadori et al. 2011). In the case of Malta and Sicily, the main producer of pistachio pollen is most probably *Pistacia lentiscus*, a thermophilous evergreen species that, in association with *Olea europaea* and *Ceratonia siliqua*, may form a veritable forest or scrub in the Thermo-Mediterranean belt, with a diverse floristic structure (Quézel and Médail 2003). This tree is currently the most frequent native pistachio species in Malta, the two other common Mediterranean species not being native (*P. atlantica*) or extremely rare (*P. terebinthus*) (Weber and Kendzior 2006).

P. lentiscus is considered as an "evolutionary anachronistic species", namely a species that has a life cycle and other biological attributes inherited from when it evolved in a different bioclimatic and biogeographical context (Verdú and García-Fayos 2002). Indeed, the reproductive cycle of this species has a mixture of tropical and Mediterranean traits that helps the species not only survive in the Mediterranean maquis but also in disturbed habitats. The flowering time of *P. lentiscus* in the southern Mediterranean is from the end of March to the beginning of May, but its vegetative development takes place during the dry summer months from the beginning of May to the end of July (Martínez-Pallé and Aronne 2000). The adult trees therefore seem resistant to relatively long summer drought because their deep root system provides access to subsoil water. The sclerophyllous leaf structure of the species, like many other Mediterranean trees, also increases its resistance to long summer droughts. The spring rainfall during the flowering period has even been suggested to limit pollination and therefore fruit formation (Martínez-Pallé and Aronne 2000). Although *P. lentiscus* seems to be highly fertile due to its numerous fruits in autumn, it has a low reproductive success because (i) many flowers never develop fruits and (ii) many fruits are seedless or are damaged by insects (Jordano 1988; Martínez-Pallé and Aronne 2000). A study of seed longevity and germination and the recruitment of *P. lentiscus* in three populations in Valencia province (eastern Spain) has shown that relatively prolonged and heavy rain events ($\geq$7 days; $\geq$100 l m^{-2}) are necessary for seed germination (García-Fayos and Verdú 1998). *P. lentiscus* also has a high resistance to freezing winter temperatures (Larcher 2000). Its distribution is, however, restricted to the Thermo-Mediterranean and less importantly to the Meso-Mediterranean zone because of the long-term phenological activity of the species, especially of female trees (a tropical trait), that exposes the vegetative and reproductive organs to frost during early winter months (Palacio et al. 2005). García-Fayos and Verdú (1998) have shown that in the semi-arid Mediterranean-type climate of Valencia (P = 400 mm/year), 62 % of the years (1950–1990) had favourable precipitation patterns for the emergence of *P. lentiscus* seedlings. Water deficit during summer drought is the main cause of mortality (90 %) of *P. lentiscus* seedlings (García-Fayos and Verdú 1998), which is not the case with already established adult trees (Martínez-Pallé and Aronne 2000). It seems that the modern frugivore avifauna of the Mediterranean region does not significantly contribute to the dispersal of the *P. lentiscus* (Jordano 1989).

Based on the above ecological review of *P. lentiscus*, it appears that the expansion of this tree may need relatively high winter temperatures, frequent and heavy rain events, but not during the flowering season (April), a short spell of summer drought for seedlings to survive, and a pre-existing tree or shrub canopy. Expansion in disturbed Mediterranean habitats in the more human-impacted Mediterranean maquis during the late Holocene cannot be excluded (e.g. Pons 1981; Verdú and García-Fayos 2002).

The rapid expansion of forest in NW Malta and southern Sicily is a regional environmental event in south-central Mediterranean probably linked to an abrupt increase of moisture availability after a relatively dry early Holocene (Noti et al. 2009; Tinner et al. 2009). Forest expansion in Malta is also correlated with a cooling event (colder waters) recorded in the marine core ODP 963 in the Sicily Channel (Fig. 2 in Incarbona et al. 2008). Furthermore, it coincides with the end of the sapropel S1 deposition in the south Adriatic Sea which was caused by the cooling of sea surface temperatures (SST), most probably during the winter to early spring (Sangiorgi et al. 2003). It has been demonstrated that sapropel deposition in the Eastern Mediterranean Sea was linked to an orbitally-controlled intensification phase of the African summer monsoon (Emeis 2007). This fact suggests that the subtropical monsoon variations can indirectly control the synoptic scale climate in the central Mediterranean by modifying the SST and the complex oceanographic circulation patterns. Outside the central Mediterranean, a mid-Holocene forest expansion has been recorded in Almería, SW Spain, dating between ca. 7950 cal. B.P./6000 B.C. and 4970 cal. B.P./3020 B.C. during which both deciduous (e.g. deciduous oak) and evergreen trees (e.g. *Pistacia*, *Olea*) expanded (Pantaléon-Cano et al. 2003). High summer temperatures and wet conditions have been suggested for this forest phase. The southeastern Iberian Peninsula has had a different vegetation and climatic history compared to more northern and interior sites (Pérez-Obiol et al. 2011). According to Tinner et al. (2009) and Magny et al. (2011), the early Holocene dry

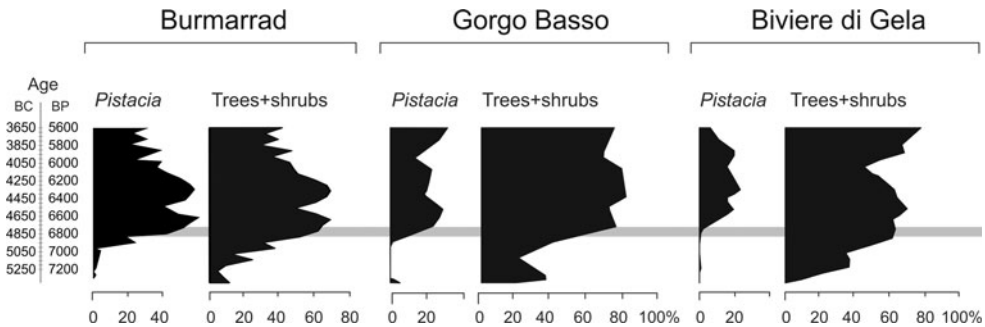

Fig. 4 Comparison of *Pistacia* and total tree pollen curves in the BM1 core with two southern Sicilian pollen records from Gorgo Basso (Tinner et al. 2009) and Biviere di Gela (Noti et al. 2009). Note the almost simultaneous expansion of *Pistacia* in all three pollen records

conditions in southern Sicily may have been linked to the strengthened Hadley circulation and subtropical monsoons that could block the moisture-bearing air masses from the North Atlantic anticyclones. Indeed, the monsoons have been shown to remotely increase the air descent in subtropical regions of SW Asia and N Africa during the boreal summer months (Rodwell and Hoskins 1996). Early Holocene monsoon intensification has also been proposed as the main cause for the delayed postglacial forest expansion in the continental inland of the Middle East (Djamali et al. 2010) and the Middle Atlas of Morocco (Tzedakis 2007). However, this long-distance effect of the monsoons may simply modify the seasonal distribution of precipitation instead of the total amount of annual precipitation (Djamali et al. 2010). As no similar early Holocene delay is observed in the forest expansion of the central and northern Italian Peninsula (e.g. Magri and Sadori 1999; Watson 1996), it seems that the latitudes around 40° N to 43° N mark the northernmost limits of the monsoonal influences on the precipitation patterns in the Mediterranean region (Magny et al. 2011; Vannière et al. 2011). The strengthened subtropical monsoons up to ca. 7000 cal. B.P. would have considerably reduced the late spring and summer rainfall in the south-central Mediterranean because of the blocking of the westward moving North Atlantic cyclonic systems. As a consequence of this event, the summer drought became longer, reducing the survival of seedlings and inhibiting any propagation of Mediterranean woody taxa including *P. lentiscus*. By ca. 7000 cal. B.P., the ITCZ shifted to lower latitudes (Fleitmann et al. 2007) and Northern Hemisphere circulation strengthened while more humid masses penetrated into the central and eastern Mediterranean through westerlies (Incarbona et al. 2008; Djamali et al. 2010), causing the shortening of the dry season and thereby the expansion of Mediterranean woodlands.

Further to the south, in NW Tunisia (at Majen Ben H'mida; 37°08′N, 09°05′ E), the early Holocene seems to have had relatively wetter conditions that favoured the expansion of semi-deciduous oak forests dominated by *Quercus canariensis* (Stambouli-Essassi et al. 2007). However, with the exception of the above site, several other palaeoecological records from the Mediterranean part of North Africa are characterized by a long hiatus with the absence of early Holocene sediments (e.g. Ben Tiba and Reille 1982; Benslama et al. 2010). The incompleteness of these records and the inadequacy of good chronologies in this region make it difficult to give any firm conclusion about the vegetation and palaeoclimatic history of this region.

Human impacts on the vegetation of NW Malta during the early to mid-Holocene transition

The onset of the human-dominated environmental change in the Mediterranean region during the mid-Holocene is not as clear as in central and NW Europe (Roberts et al. 2011; Sadori et al. 2011). In the central Mediterranean, the vegetation was mostly controlled by climatic change rather than human activities before ca. 4000 cal. B.P., even if the impact of human activities has been locally demonstrated here and there (Sadori et al. 2011). Pollen records of southern Sicily (Gorgo Basso at SW and Biviere di Gela at SE) suggest that agricultural activities had already started by the afforestation of the region around ca. 7000 cal. B.P./5050 B.C., as characterized by increased percentages of pollen associated with farming activities such as Cerealia-type, *Plantago lanceolata*-type, *Rumex acetosa*-type and *Mercurialis annua*-type pollen (Noti et al. 2009; Tinner et al. 2009). Tinner et al. (2009) suggest a moderate agricultural practice in the form of cereal (and probably fig tree) cultivation before ca. 7300–7000 cal. B.P. that decreased due to afforestation. In the Marsa area of Malta, the Cerealia-type pollen curve shows a significant increase (<8 %) by ca. 6790–6560 cal. B.P./4840–4610 B.C. followed by an increase in *Plantago lanceolata*-type pollen, suggesting that cereal farming was practiced on the island during the Ghar Dalam cultural phase at around ca. 6950–6250 cal. B.P./5000–4300 B.C. (See pollen data of F. Carroll and C. Hunt presented in Fenech 2007).

The Burmarrad BM1 pollen diagram (Fig. 3) also shows the presence of Cerealia-type and *Plantago lanceolata*-type pollen since ca. 7350 cal. B.P. suggesting that cereal farming was probably practiced by the first Neolithic communities that had already settled on the island at ca. 7400 cal. B.P./5450 B.C. (Trump 2002). The forest expansion at ca. 7000 cal. B.P. would most probably have reduced the extent of such agricultural practices with the transformation of open landscapes into forested areas as has been suggested for Gorgo Basso in SW Sicily (Tinner et al. 2009). The landscape in the catchment area of Burmarrad continued to be dominated by pistachio until ca. 6100 cal. B.P./4150 B.C. when the tree pollen values start to decline (Fig. 3). This date is approximately correlated with the beginning of the Temple cultural phase (Table 1). A slight increase in the pollen percentages of several other anthropogenic indicators is also seen at the beginning of this cultural phase (e.g. *Triticum*-type, *Plantago major–media*-type, *Rumex*, *Malva*, Brassicaceae, *Centaurea* (mainly *C. solstitialis*-type)). A significant increase in *Sporormiella*, a dung-associated fungal spore (Van Geel and Aproot 2006), is also an indication of an increased amount of livestock on the island during the Temple phase. Unfortunately, the BM1 pollen diagram terminates at ca. 5600 cal. B.P. in the middle of the Temple cultural phase.

The indicator value of some of the major pollen types in the BM1 pollen diagram is still not clear. Examples of such pollen types include *Asphodelus*, *Valerianella*, and *Theligonum*. *Asphodelus* is represented by two species on the Maltese Islands: *A. aestivus* (syn. *A. microcarpus*) and

A. fistulosus (Haslam et al. 1977; Weber and Kendzior 2006). Here we use *A. ramosus* to encompass both *A. aestivus* and *A. microcarpus,* following the typification of Díaz Lifante and Valdés (1994). *A. fistulosus* is a rare species mostly found in sheltered rocky habitats and does not appear to be an indicator of human activities (Haslam et al. 1977). However, *A. ramosus* forms large populations in nutrient deficient soils and can show overgrazing because it is not eaten by grazing animals (Weber and Kendzior 2006). The increase in pollen percentages of *Asphodelus* is associated with high values of *Pistacia* pollen suggesting an increase in humidity that in turn caused the forest expansion. This fact is somehow contradictory with the ecology of Mediterranean *Asphodelus* which are plants of open environments/steppe habitats (Grove and Rackham 2001). One way to explain the increasing *Asphodelus* pollen values is that the asphodel pollen was produced by *A. ramosus* in the slightly disturbed areas of NW Malta, which were then of limited extent compared to the vast woody areas of the island especially in the more rocky habitats. *A. ramosus* (*A. microcarpus*) represents a well-known indicator of overgrazing and man-made firing of the landscape in the semi-arid Mediterranean regions (Pantis and Margaris 1988). The simultaneous increase of *Plantago lanceolata*-type and *Rumex acetosa*-type pollen, other indicators of disturbed areas, reinforces this interpretation (Fig. 3).

Today, *Valerianella* is represented by two species in Malta, *V. eriocarpa* and *V. muricata* with the former species occurring more frequently. *V. eriocarpa* may grow in cultivated and waste lands (Haslam et al. 1977; Weber and Kendzior 2006) suggesting that the appearance and increasing values of *Valerianella* pollen since ca. 6100 cal. B.P./4150 B.C. can be interpreted with confidence as a signature of increased disturbance of natural ecosystems by human activities. Variations in *Theligonum* pollen percentages are more difficult to explain. *Theligonum cynocrambe*, the only Mediterranean species of the genus, is a common annual on the Maltese Islands especially growing on walls, derelict fields, and in rocky or stony habitats (Haslam et al. 1977). Increased values of *Theligonum* may indicate that human activities created more derelict agricultural areas and rocky/stony habitats favorable for the growth of this plant. In the flora of Syria and Lebanon, Mouterde (1966) reports that *Theligonum* is closely associated with road sides, rocky habitats, and low wall structures and has a long flowering season (January to May). In Mediterranean France and Corsica, the stony surfaces created by scree slope deposits and low wall structures separating terraced farmlands are intensively colonized by *Theligonum*. These observations, together with increasing values of cereals and other anthropogenic indicators, suggest that the *Theligonum* pollen curve, in Malta, may reflect the establishment and development of terrace agriculture, at least in the Burmarrad ria.

Local hydrological evolution

Temporal variations in the pollen of aquatic/hygrophilous plants as well as the NPPs in the BM1 diagram shed light on the local hydrological dynamics of the Burmarrad ria. The PCA Axis 1 values clearly follow the variations of aquatic versus terrestrial plants as the most important aspect of the vegetation change in the Burmarrad ria during the time interval covered by the BM1 diagram (18 % of variability). At the onset of the LPAZ BM1-A1 (Figs. 3, 5), where the sediment composition suggests an upper estuarine environment, high percentages of Cyperaceae pollen followed by *Sparganium*-type pollen (*Sparganium* spp. and/or *Typha angustifolia*) indicate the presence of terrestrial freshwater to brackish water bodies in the Burmarrad alluvial plain, which were transported into and deposited in an estuarine environment especially via fluvial systems. The presence of *Phaeoceros laevis* spores further suggests the abundance of wet acidic soils, most probably around the lakes/ponds or on the river floodplains (e.g. Sérgio 2004). This bryophyte species lives in shallow water. Very low values of dinoflagellate cysts and microforaminifera show the dominance of terrestrial rather than marine influences. The explosion of Cyperaceae pollen in the BM1-A2 subzone shows the development of a freshwater peat bog in the area by ca. 7000 cal. B.P./5050 B.C. The ecology of the identified chironomids from the peat layer interval of 1,115–1,110 cm provides more details on the palaeoenvironment contemporaneous to this short time span:

Paratendipes albimanus-type. This species is found in lowland streams and small and large rivers with their side channels but rarely in standing water (Moller Pillot and Buskens 1990). It also occurs in soft sediments in the littoral areas of mesotrophic lakes (Brodin 1986; Saether 1979). According to Rossaro (1991), *Paratendipes* spp. in Italian running waters (data set of 991 sites and 127 taxa) has an optimum water temperature of 17.3 °C (standard deviation of 2.3 °C). In Gandouin et al. (2006) the genus is considered as ubiquitous in the river chironomid typology (but towards the lotic taxa in the connection gradient between the main channel and the other floodplain water bodies).

Microtendipes pedellus-type. The genus is common in littoral and sublittoral sediments of lentic waters (Pinder and Reiss 1983), often in coarse sediments with low organic content (Hofmann 1984; Brodersen and Lindegaard 1999). Brooks and Birks (2001) consider the genus as an indicator of intermediate temperatures in northern Europe. For Rossaro (1991), *Microtendipes* spp. have an optimum water temperature of 9.1 °C (SD = 3.1 °C). It is a lentic genus in the typology of Gandouin et al. (2006).

Polypedilum. The genus is an indicator of temperate climatic conditions (Brooks et al. 2007). It is found in the littoral (Hofmann 1984) of eutrophic lakes (Klink 2002)

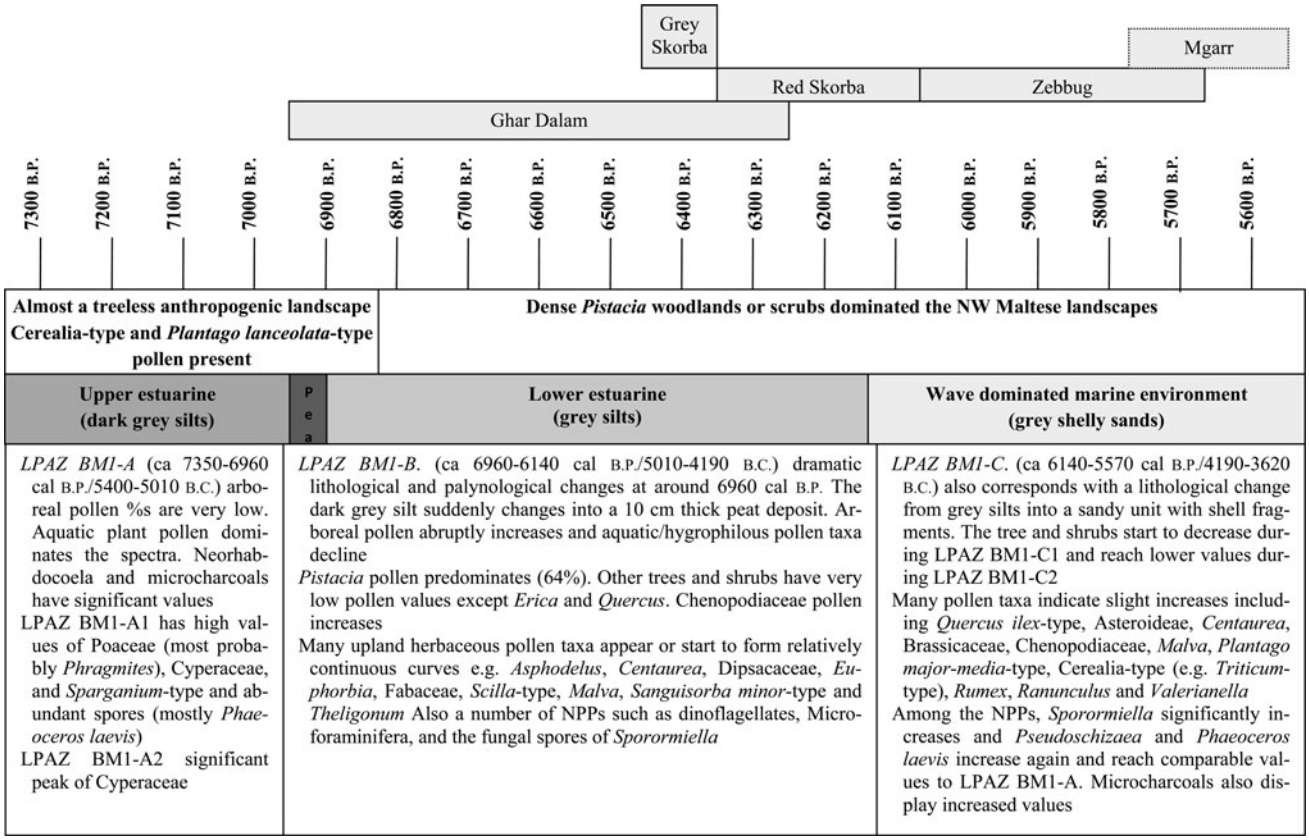

Fig. 5 Timetable comparing Local Pollen Assemblage Zones, lithological units and reconstructed vegetation types with prehistoric cultural phases of the Maltese Islands

often associated with the macrophytic vegetation (Buskens 1987; Brodersen et al. 2001). Many species are warm water species in Italian running waters (Rossaro 1991) with an optimum water temperature of 21.4 °C for *Polypedilum* spp. The genus is ubiquitous according to Gandouin et al. (2006) but towards the lentic taxa in the gradient of connection. *P. nubeculosum* has been described as a euryhaline species by Remane (Remane and Schlieper 1958). However, Tourenq (1975), in the Camargue delta, has never captured it in brackish waters but only in freshwater areas.

Parametriocnemus/*Paraphaenocladius*. The subfossil larval head-capsules of these two genera cannot be separated. However, *Parametriocnemus* and *Paraphaenocladius* both occur in streams and sometimes in the littoral zone of lakes (Moog 1995). *Paraphaenocladius* species are found in moist to wet soils (Klink and Moller Pillot 2003). According to Rossaro (1991), *Parametriocnemus* is represented by only one species: *P. stylatus* with optimum water temperatures of about 11.4 °C (SD = 4.1 °C). This species is found in springs and spring-fed upper reaches of streams (Moller Pillot and Buskens 1990).

In summary, the ecology of the chironomid assemblage found in this interval suggests a freshwater river system with low-energy flows under relatively temperate climate conditions. Waters seem to have been mesotrophic to eutrophic, with the presence of macrophytic vegetation and/or wet soils or temporary ponds on the river floodplain.

The mid-Holocene marine transgression caused an increase in the salt content of the littoral wetlands and led to the expansion of halophilous plants such as Chenopodiaceae (LPAZ BM1-B1). Increased values of halophilous Chenopodiaceae pollen in coastal fluvio-deltaic complexes are a common feature of marine inundation phases (e.g. Gandouin et al. 2009) which result in the formation of estuarine brackish marshes. A continued rise of sea water established a true marine environment (lower estuarine environment) at the site of BM1 at ca. 6900 cal. B.P./4950 B.C. characterized by increasing values of dinoflagellates and microforaminifera. These depositional conditions persisted up to the top of the diagram. The reappearance of *Phaeoceros laevis* spores during the LPAZ BM1-C may be linked to human activities as this species is also known as "segetal" or farming-associated (Auguier 1966). Its spores may have been transported into the Burmarrad upper estuarine environment by surface runoff. This hypothesis is reinforced when the variations of some NPPs and pollen taxa are considered (see the above section). In a coastal wetland in SE Spain, a *Pseudoschizaea* (formerly *Concentricystes*) increase has been attributed to

both warm temperatures with seasonal drying and also increased input of minerogenic sediments via fluvial systems (e.g. Carrión and Navarro 2002). In the Black Sea, it has been found in the late Holocene layers, while in the early Holocene brackish waters of the same basin it has not been found (Mudie et al. 2011). This may suggest a link with increased anthropogenic activities in the Black Sea drainage basin. Its increase in the Burmarrad palaeo-estuarine environment may thus be better interpreted as being related to a slight increase in soil erosion due to human activities in accordance with other anthropogenic indicators.

Conclusions

The main trends of vegetation change in NW Malta during the early to mid-Holocene transition were similar to other regional vegetation records from the south-central Mediterranean region, especially those of coastal Sicily characterized by the transformation of a steppe-like vegetation/garrigue into a dense shrubland/maquis dominated by evergreen *Pistacia*. Differences in the vegetation dynamics seem to be mostly linked to the different phytogeographical and floristic contexts of Malta in relation to neighboring areas. The ca. 2,000-year pollen record presented in this study shows that the potential natural vegetation of the Maltese islands in the absence of human pressure is not necessarily an evergreen oak forest dominated by *Quercus ilex*, but can be a Mediterranean evergreen shrubland or small woodland comprising *Pistacia* cf. *lentiscus* and most probably other insect-pollinated trees and shrubs not represented in the pollen assemblages (e.g. *Ceratonia siliqua*).

Malta and Sicily are located at a key climatic point in the central Mediterranean because the Holocene climatic history shows different palaeohydrological patterns, to the north and south of their latitudinal position. Their different vegetation and hydrological dynamics may reflect a stronger effect of the strengthened subtropical monsoon systems during periods of the Northern Hemisphere boreal solar insolation maxima. Although the traces of human activities in the studied area are evident from the beginning of the diagram at ca. 7350 cal. B.P./5350 B.C., human presence has become more evident since the beginning of the Temple cultural phase at ca. 6050 cal. B.P./4100 B.C. through a conspicuous reduction in tree pollen and increasing values of anthropogenic pollen indicators of overgrazing and soil erosion. As with coastal Sicily, we suggest that the early- to mid-Holocene vegetation transformation was mainly controlled by a regional climatic change that occurred in a landscape only slightly impacted by human activities.

Acknowledgments This study was supported by the PALEOMED project (ANR 09-BLAN-0323-204 01) financed by the French National Research Agency. The first author wishes to thank Laurent Londeix, Maria Sanchez Goñi, Jean-Louis Turon, and Frédérique Eynaud from EPOC, for their hospitality and valuable advice on dinoflagellate identification and scientific discussions during his research stay at the University of Bordeaux in January 2011. We are also thankful to Willy Tinner for his invaluable comments on the BM1 pollen diagram and Arne Saatkamp for his assistance with botanical interpretation of the diagram. Constructive and thoughtful comments of the two reviewers of this paper are greatly appreciated.

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